

Interaction of Elastic Waves with Corrosion Damage

E. D. SWENSON, M. P. DESIMIO, S. E. OLSON
AND H. SOHN

ABSTRACT

Corrosion inspection and repair accounts for 21% of the total maintenance costs averaged over the Army, Navy, and Marine air and ground vehicles. A reliable automated method for inspection can lead to cost reductions due to avoiding unnecessary tear down and re-assembly. Elastic waves can travel across relatively large distances in plate-like structures and are affected by the presence of corrosion. This paper presents an investigation of the interaction of elastic waves with induced corrosion damage in an aluminum plate using a three-dimensional laser Doppler vibrometer (3D-LDV). The investigation begins with measurements of elastic waves propagating through an aluminum plate. The 3D-LDV provides both in- and out-of-plane velocity components for a uniform grid of approximately 40,000 points with approximately 2.2 mm spacing between grid points in the x - and y -directions. Images created from the 3D-LDV measurements clearly show the interaction of the elastic wave energy with the corrosion. Comparisons between the in- and out-of-plane components provide insight into whether symmetric or antisymmetric Lamb wave modes are better for detecting corrosion damage.

INTRODUCTION

Corrosion inspection and repair accounts for 21% of the total maintenance costs averaged over the Army, Navy, and Marine air and ground vehicles [1]. A reliable automated method for inspection can lead to cost reductions due to avoiding unnecessary tear down and re-assembly. Elastic waves can travel across relatively large distances in plate-like structures and are affected by the presence of corrosion. This paper presents an investigation of the interaction of elastic waves with induced corrosion damage in an aluminum plate using a three-dimensional (3D) laser Doppler vibrometer (LDV).

This paper studies the interaction of elastic waves with corrosion in aluminum plates. The use of elastic waves has shown promise in detecting highly localized

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE AUG 2010		2. REPORT TYPE N/A		3. DATES COVERED -	
4. TITLE AND SUBTITLE Interaction of Elastic Waves with Corrosion Damage				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air Force Institute of Technology, Wright-Patterson AFB, OH, USA				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited					
13. SUPPLEMENTARY NOTES See also ADA539605. European Workshop on Structural Health Monitoring (5th) (EWSHM 2010) Held in Naples, Italy on June 29-July 2, 2010. Journal Articles; U.S. Government or Federal Purpose Rights License., The original document contains color images.					
14. ABSTRACT Corrosion inspection and repair accounts for 21% of the total maintenance costs averaged over the Army, Navy, and Marine air and ground vehicles. A reliable automated method for inspection can lead to cost reductions due to avoiding unnecessary tear down and re-assembly. Elastic waves can travel across relatively large distances in plate-like structures and are affected by the presence of corrosion. This paper presents an investigation of the interaction of elastic waves with induced corrosion damage in an aluminum plate using a three-dimensional laser Doppler vibrometer (3D-LDV). The investigation begins with measurements of elastic waves propagating through an aluminum plate. The 3D-LDV provides both in- and out-of-plane velocity components for a uniform grid of approximately 40,000 points with approximately 2.2 mm spacing between grid points in the x- and y-directions. Images created from the 3D-LDV measurements clearly show the interaction of the elastic wave energy with the corrosion. Comparisons between the in- and out-ofplane components provide insight into whether symmetric or antisymmetric Lamb wave modes are better for detecting corrosion damage.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 6	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

damage, such as cracking or delamination, due to the relatively short wavelengths of the propagating waves. Lamb waves offer several advantages for structural health monitoring (SHM), such as the ability to propagate over relatively large distances, which improves the ability to monitor large areas for relatively small damage, and to provide through-thickness interrogation, which may be of particular importance when internal defects occur. Staszewski, *et al.* [2-5] have demonstrated the potential of using laser vibrometry to detect fatigue cracking in metallic structures. The use of 3D LDV scans provides in- and out-of-plane velocity components over the entire scanned region.

Initial studies, discussed below, have been performed on an aluminum plate test article. Details on the experimental setup and laser vibrometer testing are provided. Experimental results are presented and discussed. Finally, conclusions and recommendations based on these studies are presented.

EXPERIMENTAL TESTING

The test article used for the initial studies is a sheet of 6061-T6 aluminum with a height of 609 mm, width of 609 mm, and thickness of 3.175 mm. One piezoelectric sensor is bonded to the center of one face of the plate using M-Bond 200 cyanoacrylate strain gage adhesive. The sensor is a 6.35 mm diameter piezoceramic disk with a thickness of 0.25 mm encapsulated in a Kapton protective layer that also contains electrical traces to provide or sense a voltage across the thickness of the sensor. Figure 1 shows a photograph and schematic of the test article. Simulated corrosion has been created on one surface of the plate using a 30% hydrochloric acid solution. Varying the area of exposure, exposure time, and temperature provides depths of approximately 1.0, 2.0, and 3.0 mm at the locations shown in Figure 1(b). Close-up photographs of the simulated corrosion areas are shown in Figure 2. Considerable variation in the surface texture can be seen, particularly for the areas with greater depths. For the 3.0 mm deep simulated corrosion area at Location 3, through holes have been created at several locations within the corroded region as seen in the lower left portions of Figure 2(c).

For the experimental testing, a Hamming-windowed, 5½-cycle sine burst excitation signal is generated using an Agilent 33120A waveform generator. A Krohn-Hite 7500 power amplifier is used to amplify the excitation signal to a peak-

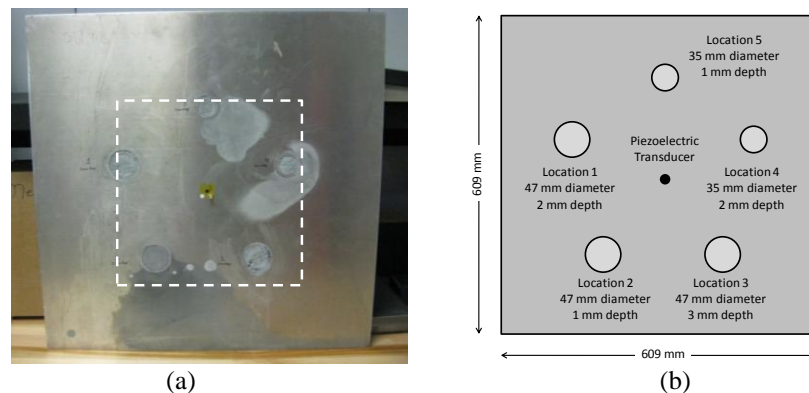


Figure 1. (a) Photograph of back side of test article and (b) schematic identifying simulated corrosion areas (not to scale)

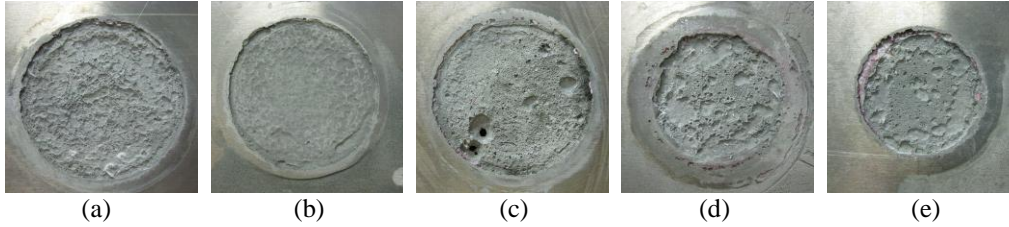


Figure 2. Close-up photographs of simulated corrosion damage at (a) Location 1; (b) Location 2; (c) Location 3; (d) Location 4; and, (e) Location 5 (photos individually scaled)

to-peak voltage of approximately 100 V and applied directly to the piezoelectric sensor. In prior experiments [6], pitch-catch testing was performed to create Lamb wave mode tuning curves to identify appropriate frequencies to generate A_0 , S_0 , or both modes. It was determined that excitation at a center frequency of 100 kHz dominantly excites the A_0 mode, and at 250 kHz, contributions from the S_0 and A_0 modes are approximately equivalent. To dominantly excite the S_0 mode, a center frequency near 300 kHz should be used. A laser Doppler vibrometer (LDV) is used to measure the elastic waves as they travel through the plate and interact with the damaged areas which is described next.

LDV data collection is performed using a Polytec High Frequency PSV-400-3D-M Scanning Vibrometer system designed for full-field vibration measurements for frequencies up to 1 MHz. The system consists of a motorized PSV-A-T31 tripod, supporting three separate PSV-I-400 sensor heads, as well as a high-resolution camera that provides the capability to make precise corrections to the measurement points in 3D. Surface velocity measurements are made by evaluating the Doppler frequency shift of a laser beam reflected from the test article. For 3D measurements, surface velocities are recorded using three lasers coincident at a point on the surface of the plate. These measurements can be resolved onto a 3D orthogonal coordinate system after the measurement and laser head locations are determined through calibration procedures. Thus, the system allows for fast, precise, non-contact 3D measurements, with a complete resolution of 3D velocity vectors with respect to a Cartesian coordinate system. The face of the plate on the opposite side of the corrosion and sensor is scanned by the LDV. The region scanned by the laser is indicated by the square region in Figure 1(a). For more accurate LDV measurements, the scanned area of the aluminum plate is coated with Magnaflux SKD-S2 SpotCheck developer, an aerosol spray of white developing particles in a fast drying solvent.

During LDV scanning, measurements are taken over the 400 mm by 400 mm scan region shown in Figure 1. For each measurement, 512 samples are collected at a 2.56 MHz sample rate, providing in 200 μ s of data. A 2.2 mm grid spacing is utilized, resulting in scans containing approximately 40,000 measurement points. At each grid point, 70 responses are averaged to improve the signal to noise ratio of the measurements. During averaging, an appropriate delay between each excitation allows responses to decay to levels similar to ambient noise. The results of the LDV measurements are velocity time histories at the set of specified grid locations on the scanned face of the plate.

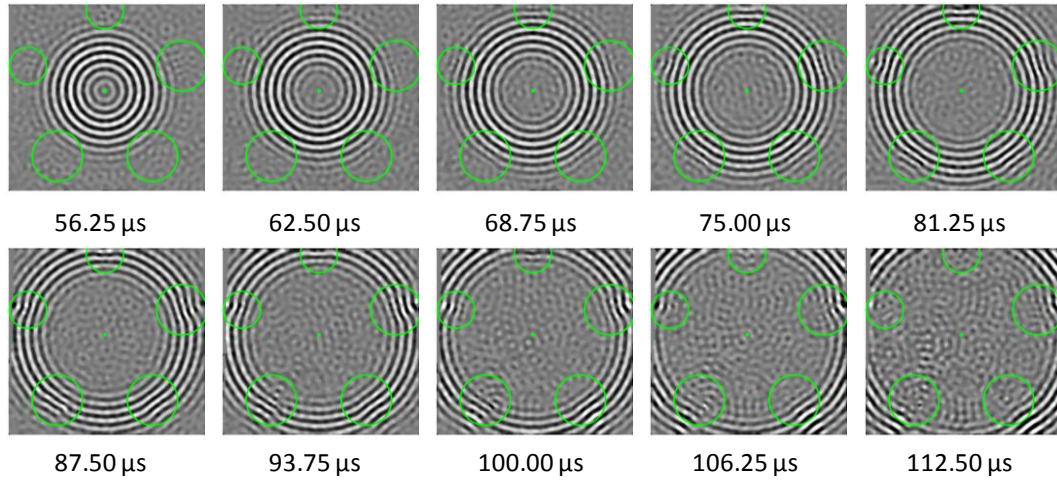


Figure 3. Processed out-of-plane velocity components from experimental LDV testing for 100 kHz excitation at various times after the start of the excitation signal

RESULTS

Time histories can be processed to produce a sequence of velocity field images showing elastic wave propagation across the plate and the interaction with the damaged locations. The images have been up-sampled to improve the visual quality. To reduce noise in the measurements, the up-sampled images are then median filtered. The median filter replaces the measured value at each grid point with the median value of the measurements in the 11 by 11 pixel neighborhood around the grid point. Additionally, amplitude scaling is performed to ease visual comparison of results. Because some grid points are directly behind the excitation source, and because interesting wave structures exist at low amplitudes, normalization is necessary. In this work, a maximum absolute velocity value, v_{\max} , is selected and measurements with values beyond these limits are set to $\pm v_{\max}$. Although this leads to saturated values at early observation times, it allows visual observation of details at later times when the wave energy is distributed across the scan region. The selection of v_{\max} has been based on the central 95th percentile of the absolute velocity values over all measurements in an image at 100 μs . Final images are formed by scaling and shifting these threshold images, and then displaying gray scale images where black corresponds to $-v_{\max}$ and white to $+v_{\max}$.

Figure 3 shows a sequence of out-of-plane velocity measurements over the entire LDV scan region. The front side of the plate is scanned, so the corrosion regions are flipped left-right from those in Figure 1. Propagation of the A_0 mode can clearly be observed in the sequence of images. As seen in the figure, the A_0 mode slows as the waves propagate through the corrosion regions. The S_0 mode propagation is not evident, but could contribute to the background noise seen in the images.

To better illustrate the effect of the simulated corrosion areas on the A_0 wave propagation, Figure 4 provides detailed views of the out-of plane velocity fields around each damage location. The sequence of images show the A_0 waves entering each corroded region, slowing as they propagate through the region, and then exiting the region. Location 3, with an approximate corrosion depth of 3 mm

appears to have the largest slowing effect on the wave behavior. A reduced effect is observed in Locations 2 and 4, which have approximate corrosion depths of 2 mm. Lastly, a less pronounced, but still detectable, effect is seen in for the 1 mm corrosion depths at Location 1 and 5. Interestingly, few reflections are seen as the waves enter or leave a corroded region.

DISCUSSION

Processed images from the LDV scans show that the simulated corrosion regions affect elastic wave propagation. As shown in Figures 3 and 4, A_0 wave propagation at 100 kHz slows as the wave enters the corroded regions. At 100 kHz, the A_0 mode is operating in a range of the group velocity dispersion curve where changes to the frequency-thickness product can significantly affect the wave speed. Little effect on the S_0 mode is seen since this mode is operating in a range where changes in the frequency-thickness product have minimal effect on the wave speed.

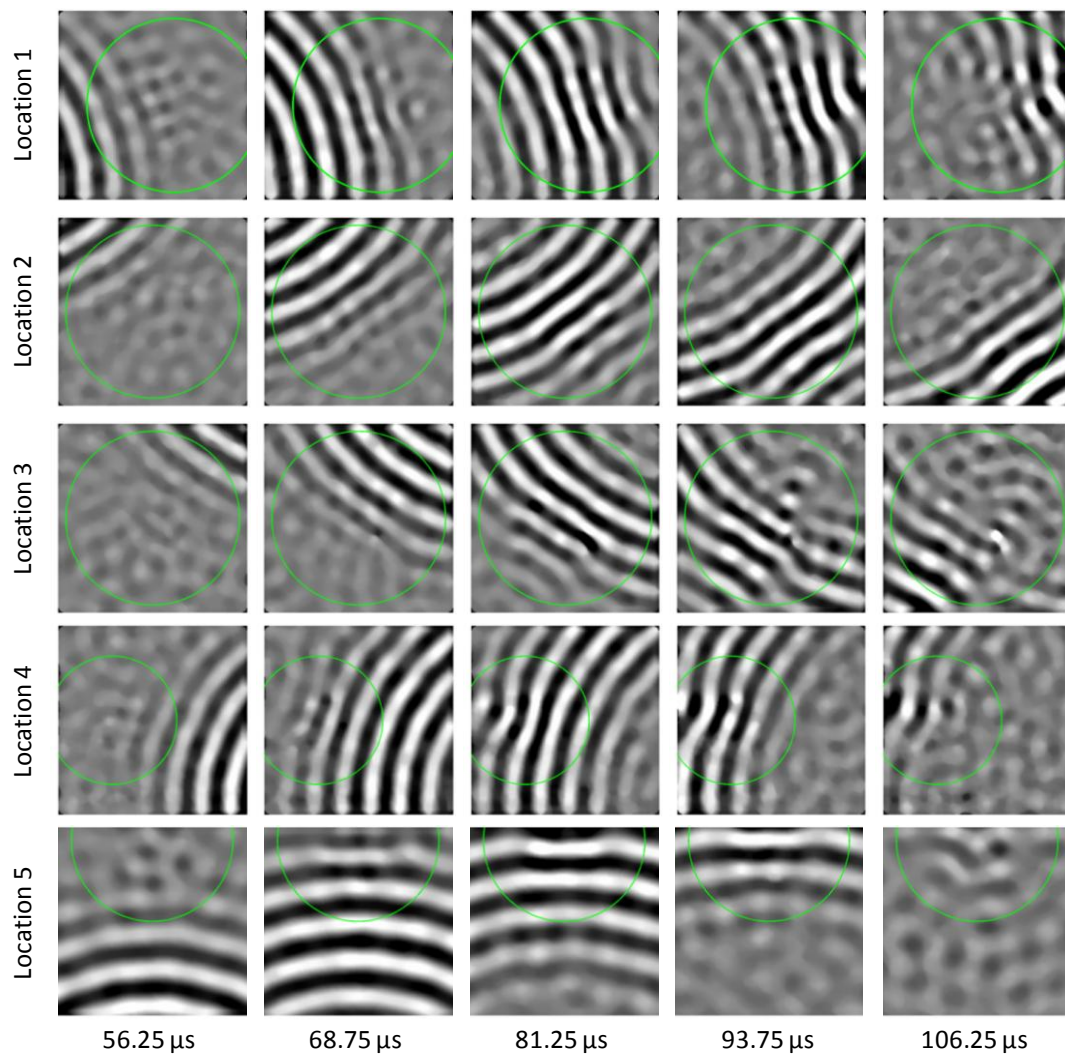


Figure 4. Processed out-of-plane velocity components around simulated corrosion locations for 100 kHz excitation at various times after the start of the excitation signal

At higher excitation frequencies, the effect of the S_0 mode may be increased. However, the flexural behavior of the A_0 mode may make it easier to discern changes than if the S_0 mode is utilized, particularly if the out-of-plane velocity components are used. Additional investigations are being performed to determine optimal excitation frequencies to highlight simulated corrosion damage of various thicknesses.

CONCLUSIONS

Corrosion damage is a major cost driver for the maintenance of military air and ground vehicles. A reliable automated method for inspection could lead to significant cost reductions through the avoidance of unnecessary tear down and re-assembly. Elastic waves have shown potential for corrosion detection. This paper explores the potential use of piezo-generated Lamb waves to detect simulated corrosion damage by examining full-field velocity scans from 3D LDV measurements. Scans of the out-of-plane velocity components of the A_0 mode at 100 kHz clearly indicate the simulated damage. However, even for relatively large corroded thicknesses, the changes in the wave propagation behavior are relatively minor. Further studies are warranted and should include consideration of both the A_0 and S_0 modes, as well as the in-plane velocity components.

ACKNOWLEDGMENTS

The efforts of S. Olson and M. DeSimio have been funded by the Air Force Research Laboratory (AFRL) under Contract Number FA8650-04-D-3446. The support of Mark Derriso, Matthew Leonard, and Kevin Brown of AFRL is greatly appreciated. Special thanks goes to Jay Anderson for lab support and Sydney Swenson whose brilliant experimental insights made this work possible.

REFERENCES

1. Herzberg, E., "Cost of Corrosion," presented at the 40th Air Force Corrosion Program Conference, Warner Robins, GA, March 24-27, 2009.
2. Leong, W.H., W.J. Staszewski, B.C. Lee and F. Scarpa, "Structural health monitoring using scanning laser vibrometry: III. Lamb waves for fatigue crack detection," *Smart Materials and Structures*, **14**, pp. 1387-1395, 2005.
3. Lee, B.C. and W.J. Staszewski, "Lamb wave propagation modelling for damage detection: I. Two-dimensional analysis," *Smart Materials and Structures*, **16**, pp. 249-259, 2007.
4. Lee, B.C. and W.J. Staszewski, "Lamb wave propagation modelling for damage detection: II. Damage monitoring strategy," *Smart Materials and Structures*, **16**, pp. 260-274, 2007.
5. Staszewski, W.J., B.C. Lee and R. Traynor, "Fatigue crack detection in metallic structures with Lamb waves and 3D laser vibrometry," *Meas. Science and Technology*, **18**, pp. 727-739, 2007.
6. Underwood, R., "Damage detection analysis using Lamb waves in restricted geometry for aerospace applications," Master's Thesis, Air Force Institute of Technology, March 2008.